# Searching for cosmic missing baryons with DIOS – Diffuse Intergalactic Oxygen Surveyor –


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Approximately 30 to 50 percent of the total baryons in the present universe is supposed to take a form of warm/hot intergalactic medium (WHIM) whose X-ray continuum emission is very weak. In order to carry out a direct and homogeneous survey of elusive cosmic missing baryons, we propose a dedicated soft-X-ray mission, *DIOS* (Diffuse Intergalactic Oxygen Surveyor). The unprecedented energy resolution ($\sim$ 2eV) of the XSA (X-ray Spectrometer Array) on-board *DIOS* enables us to identify WHIM with gas temperature $T = 10^{6-7}$K and overdensity $\delta = 10 - 100$ located at $z < 0.3$ through emission lines of OVII and OVIII. *DIOS*, hopefully launched in several years, promises to open a new window of detection and characterization of cosmic missing baryons, and to provide yet another important and complementary tool to trace the large-scale structure of the universe.


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## I. INTRODUCTION

It is widely accepted that our universe is dominated by *dark* components; 23 percent in dark matter, and 73 percent in dark energy [1]. More surprisingly, as Fukugita, Hogan & Peebles (1998) pointed out earlier[2], even the remaining 4 percent, cosmic baryons, has largely evaded the direct detection so far, i.e., most of the baryons is indeed *dark* (see Fig.1). Those *cosmic missing baryons* may consist of compact stellar objects (white dwarfs, neutron stars and black holes), brown dwarfs, and/or diffuse gas.

Subsequent numerical simulations[3, 4] indeed suggest that approximately 30 to 50 percent of total baryons at $z = 0$ take the form of the warm-hot intergalactic medium (WHIM) with $10^5\text{K} < T < 10^7\text{K}$ which does not exhibit strong observational signature. Figure 2 depicts snapshots of distribution of different species of matter in the universe at $z = 0$ from a smoothed hydrodynamic simulation in a $\Lambda$ CDM universe [6];$\Omega_{\rm m} = 0.3$, $\Omega_{\rm b} = 0.015h^{-2}$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 1.0$, and $h = 0.7$, where $\Omega_{\rm m}$ is the density parameter, $\Omega_{\rm b}$ is the baryon density parameter, $\Omega_\Lambda$ is the dimensionless cosmological constant, $\sigma_8$ is the rms density fluctuation top-hat smoothed over a scale of $8h^{-1}$Mpc, and $h$ is the Hubble constant in units of 100 km/s/Mpc. It employs $128^3$ dark matter particles and the same number of gas particles in a comoving simulation cube of $L^3_{\rm box} = (75h^{-1}\text{Mpc})^3$. Clearly WHIM ($10^5\text{K} < T < 10^7\text{K}$; *lower right*) traces the large-scale filamentary structure of mass (dark matter) distribution (*Upper left*) more faithfully than hot intracluster gas ($T > 10^7$K; *Lower left*) and galaxies (*Upper right*) both of which preferentially resides in clusters that form around the knot-like intersections of the filamentary regions. This implies that WHIM carries important cosmological information in a complementary fashion to distribution of galaxies (in optical) and of clusters (in X-ray).

Unfortunately the conventional X-ray emission of WHIM via the thermal bremsstrahlung is very weak, and its detection has been proposed only either through the OVI absorption features in the QSO spectra or the possible contribution to the cosmic X-ray background in the soft band. Those attempts, however, are not well suited for unbiased exploration of WHIM that is important for cosmological studies. In Ref.[7], we have proposed to survey WHIM using oxygen emission lines.


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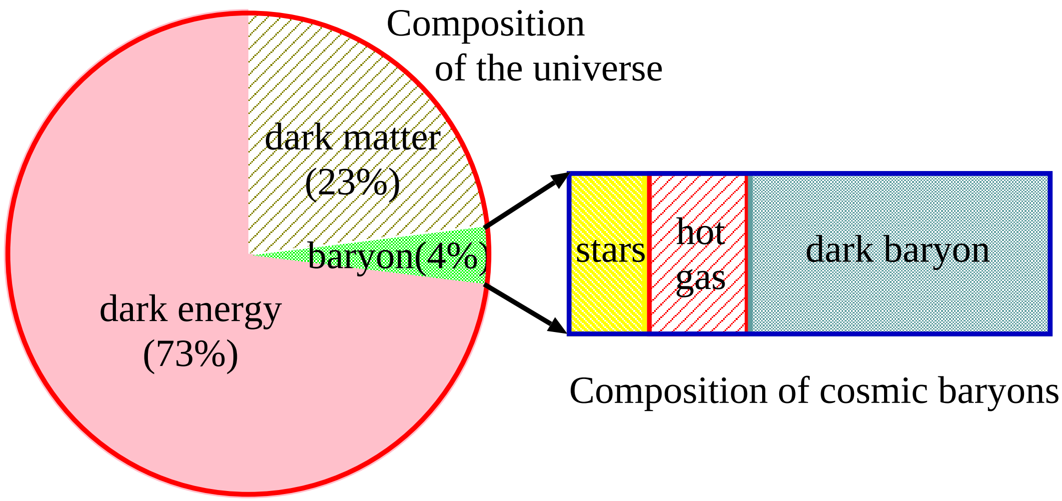


FIG. 1: Composition of the universe and cosmic baryons

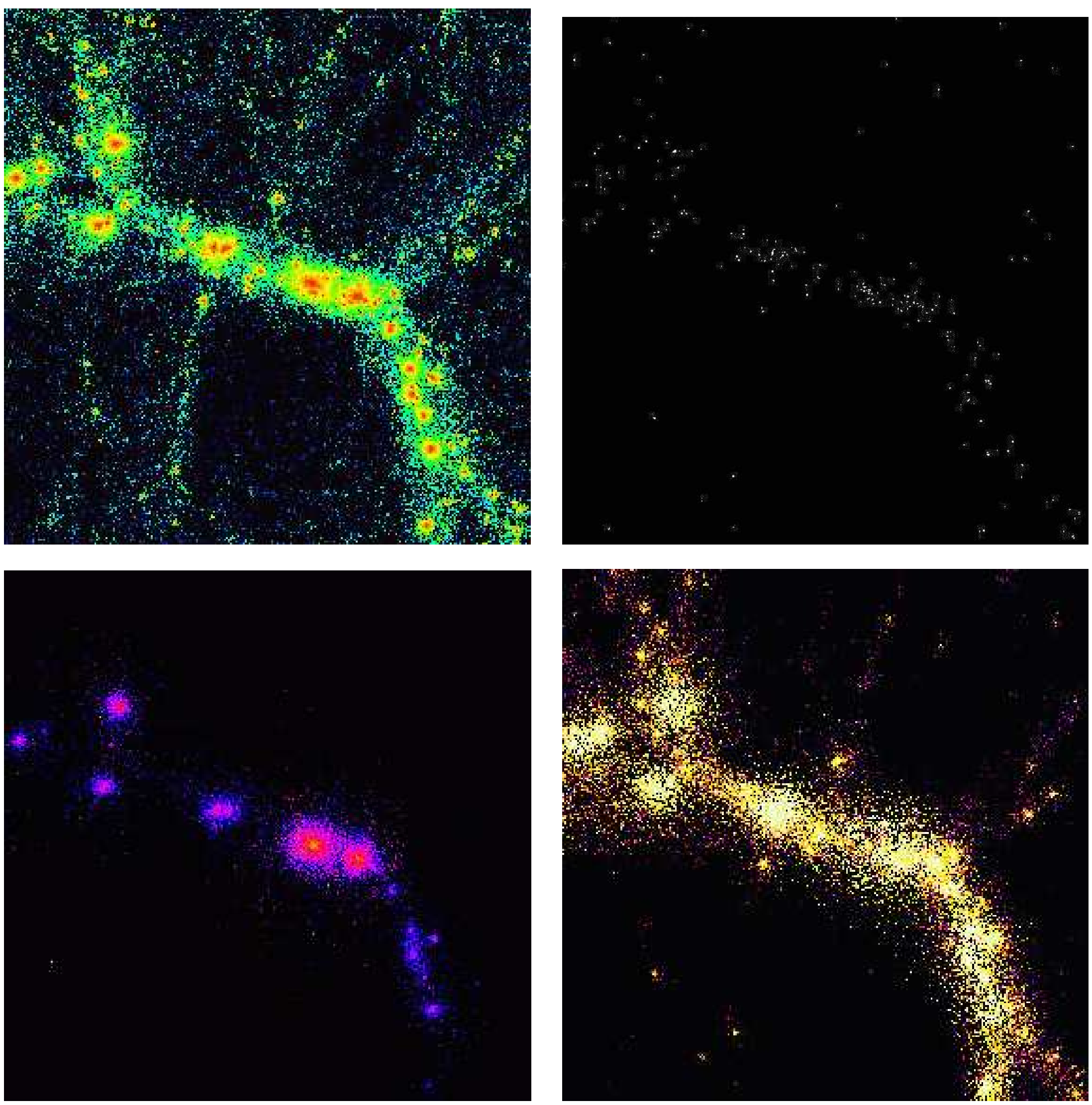

FIG. 2: Simulated distribution of matter in the universe; *Upper-left:* dark matter, *Upper-right:* galaxies (cold baryon clumps below $T^4$K), *Lower-left:* hot intra-galactic medium ($T > 10^7$K), and *Lower-right:* warm-hot intergalactic medium ($10^5\mathrm{K} < T < 10^7$K). The size of the plotted boxes corresponds to $30h^{-1}$Mpc $\times 30h^{-1}$Mpc with the depth of $10h^{-1}$Mpc.

On the basis of this study, we propose a dedicated soft-X-ray mission, *DIOS* (Diffuse Intergalactic Oxygen Surveyor), which aims at performing a direct and homogeneous survey of WHIM that is supposed to constitute the major fraction of cosmic missing baryons.

The detectability of oxygen emission lines with *DIOS* and the current technical progress are discussed in Ref.[7] and Ref.[9], respectively.

## II. DIOS

We propose *DIOS* for a small satellite program which is a new scheme under consideration by ISAS/JAXA. The primary scientific purpose is a systematic sky survey of WHIM using oxygen K emission lines, OVII (561eV:1s$^2$–1s2s), OVII (568eV:1s$^2$–1s2p), OVII (574eV:1s$^2$–1s2p), OVII (665eV:1s$^2$–1s3p) and OVIII (653eV:1s–2p). Thus both unprecedented energy resolution ($\Delta E \approx 2$ eV) and large field of view are required. These features will be made possible by a combination of two innovations; a 4-stage X-ray telescope and a large array of TES (Transition Edge Sensor) micro-calorimeter. *DIOS* will also perform a mapping observation of the hot interstellar medium in our Galaxy. Taking advantage of the high energy-resolution, *DIOS* can detect the Doppler shifts of the hot interstellar gas with a velocity $\sim$ 100 km s$^{-1}$, directly revealing the dynamics of heavy elements in hot bubbles in our Galaxy (galactic fountain).

TABLE I: *DIOS* Mission summary

| | |
|---|---|
| Four-reflection X-ray telescope | |
| FOV×effective area | $S\Omega$ =100 cm$^2$deg$^2$ at 0.6 keV |
| angular resolution | $\sim$ 3 arcmin |
| X-ray imaging spectrograph | |
| energy range | 0.3keV $< E <$ 1keV |
| energy spectral resolution | 2eV |
| size of detector | >10mm×10mm |
| number of pixels | $\sim$16×16 |
| FOV | $\sim 50' \times 50'$ |
| Satellite system | |
| orbit lifetime | $>$ 1 year |
| position control accuracy | $<$ 0.5 arcmin |
| weight | $<$ 400 kg |

### A. Spacecraft

Figure 3 shows a schematic view of the *DIOS* spacecraft. Table I summarizes our proposed features of *DIOS* for the successful WHIM detection (see the next section). The spacecraft will weigh about 400 kg in total including the payload of $\sim$ 280 kg. Thus the mission may be launched also as a piggy-back or sub-payload in H2 or Ariane rockets. It is also possible for a launch with the new ISAS rocket, such as M-V light. The size before the launch is 1.5 × 1.5 × 1.2 m, and the 1.2 m side will be expanded to about 6 m after the paddle deployment.

The total power required is 500 W, of which 300 W is consumed by the payload. The nominal orbit is a near earth circular one with an altitude of 550 km. This low-earth orbit can be reached by the ISAS rocket M-V light. An alternative choice of the orbit under consideration is an eccentric geostationary transfer orbit. This orbit gives a lower heat input from the earth and relaxes the thermal design of the satellite, and would enhance the launch opportunity to be carried as a sub-payload for geostationary satellites. One significant drawback in this case, however, is the increased particle background level as already experienced by Chandra and XMM-Newton. In the soft energy range below 1 keV, electrons can be a major source of background.

The attitude will be 3-axis stabilized with momentum wheels. Typical pointing accuracy will be about $10''$. The direction of the field-of-view can be varied within $90^\circ \pm 20^\circ$ from the Sun's direction. With this constraint, any position in the sky can be accessed within half a year.

### B. Instruments

Several new technologies will be introduced in the *DIOS* mission. The 4-stage X-ray telescope FXT (Four-stage X-ray Telescope) is the first one [8]. As shown in Fig. 4, incident X-rays are reflected 4 times by thin-foil mirrors and are focused at only 70 cm from the mirror level. At the energy of oxygen lines, $\sim$ 0.6 keV, the reflectivity of the mirror surface is as high as 80% and the reduction of the effective area is not a serious problem. The 4-stage reflection makes the focal length around 50 percent of that in the usual 2-stage design, substantially reducing the volume and weight of the satellite. Also, a relatively small focal plane detector can have a wide field of view, which is a great advantage for a TES calorimeter array. In our basic design, the outer diameter of the mirror and the effective area are 50 cm and 400 cm$^2$, respectively, at 0.6 keV. Ray-tracing simulation indicates that the angular resolution of is 2 arcmin (half-power diameter), and the image quality does not show significant degradation at an offset angle $30'$. This 4-stage telescope is a key design factor in making *DIOS* accommodated in the small satellite package.

The focal plane instrument XSA (X-ray Spectrometer Array) is an array of TES micro-calorimeters, whose development in Japan is our collaboration with Waseda University, Seiko Instruments Inc., and Mitsubishi Heavy Industries. There will be 16 × 16 pixels covering an area of about 1 cm$^2$. The corresponding field of view is $50'$. XSA will have an energy resolution of 2 eV (FWHM at 0.6 keV). We are now developing several new techniques toward the multi-pixel operation of TES calorimeters. X-ray absorbing material under consideration is Bi, which has low heat capacity and does not produce long-living

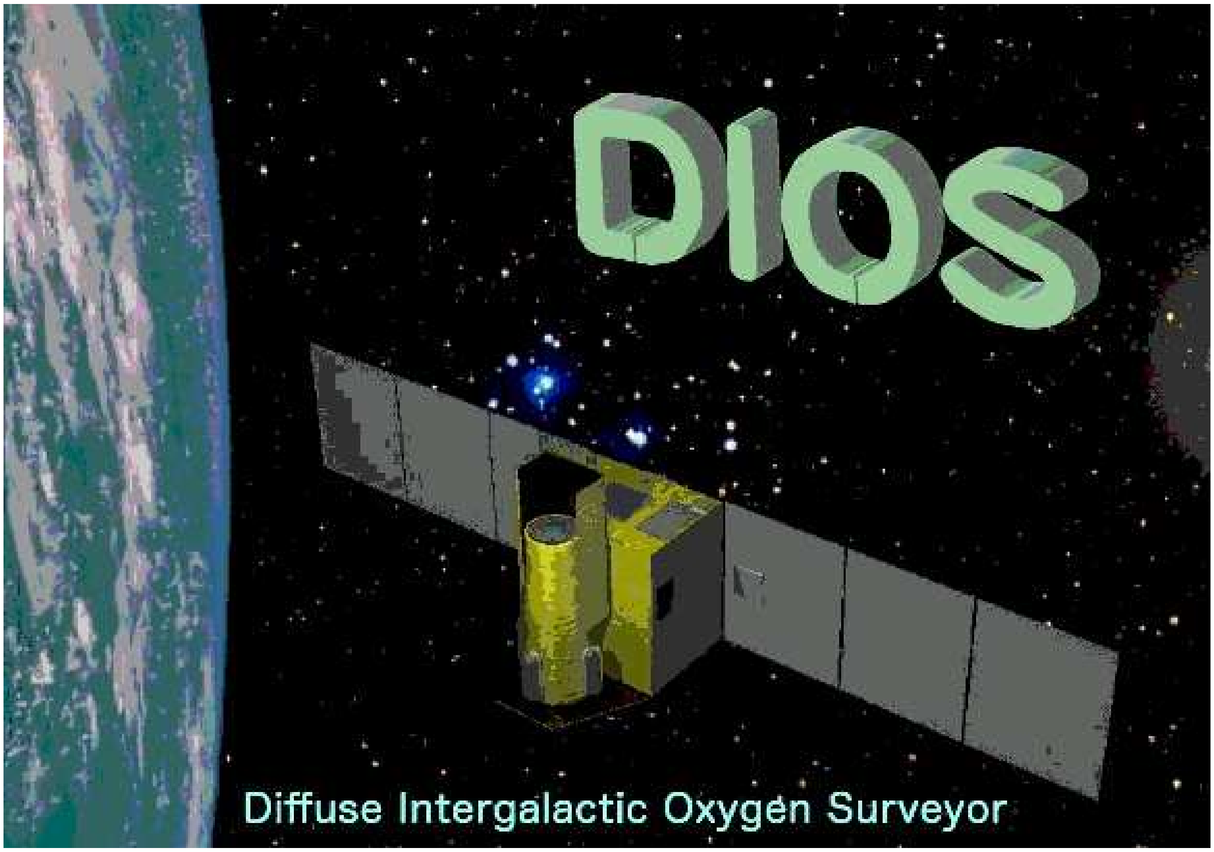


FIG. 3: A dedicated soft X-ray mission to search for dark baryons via oxygen emission lines, *DIOS* (Diffuse Intergalactic Oxygen Surveyor). The length of the solar paddle is 6 m.

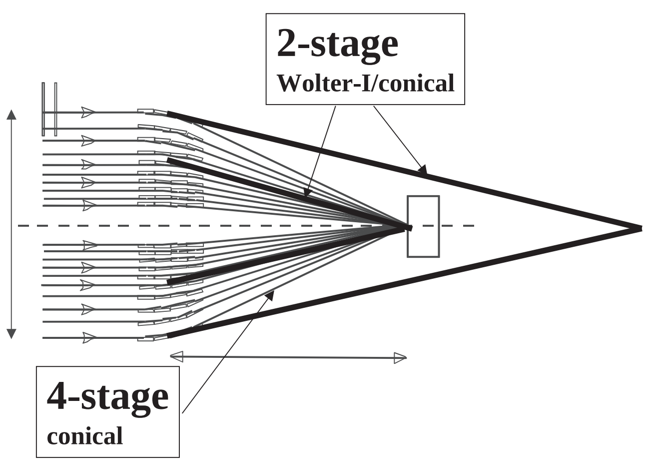


FIG. 4: Concept of the 4-stage reflection telescope.

quasi particles in the absorber. We are testing an electroplating method to build a $16 \times 16$ array with a pixel size $\sim 0.5 \times 0.5$ mm supported by a thin stem. For the signal readout, efficient multiplexing of the signals is essential to take out all the data from the cold stage. We are trying to add the signals in frequency space by operating the TES calorimeters with AC bias at different frequencies. We were successful in decoding signals from 2 different pixels so far. A new multi-input SQUID has also been developed to add the signals from several TES pixels together. An efficient thermal shield with high soft X-ray transmission is an essential item, and we are considering very thin Be foils for this purpose.

Another important feature of *DIOS* is the cryogen-free cooling system. We are considering a serial connection of different types of coolers to achieve $\sim 50$ mK for XSA within the available power budget. In the first stage, a Stirling cooler takes the temperature down to 20 K, and then $^3$He Joule-Thomson cooler reduces it to 1.8 K as the second stage. The third stage is $^3$He sorption cooler achieving 0.4 K, and finally adiabatic demagnetization refrigerator obtains the operating temperature at 50 mK. Since no cryogen is involved, this cooling system ensures an unlimited observing life in the orbit, which is a big advantage of *DIOS*. The XSA system is subject to a warm launch, therefore we have to allow for the initial cooling of the system for the first 3 months in the orbit.

Since several challenging technologies are involved, we seriously consider international collaboration in various parts of the observing instruments.

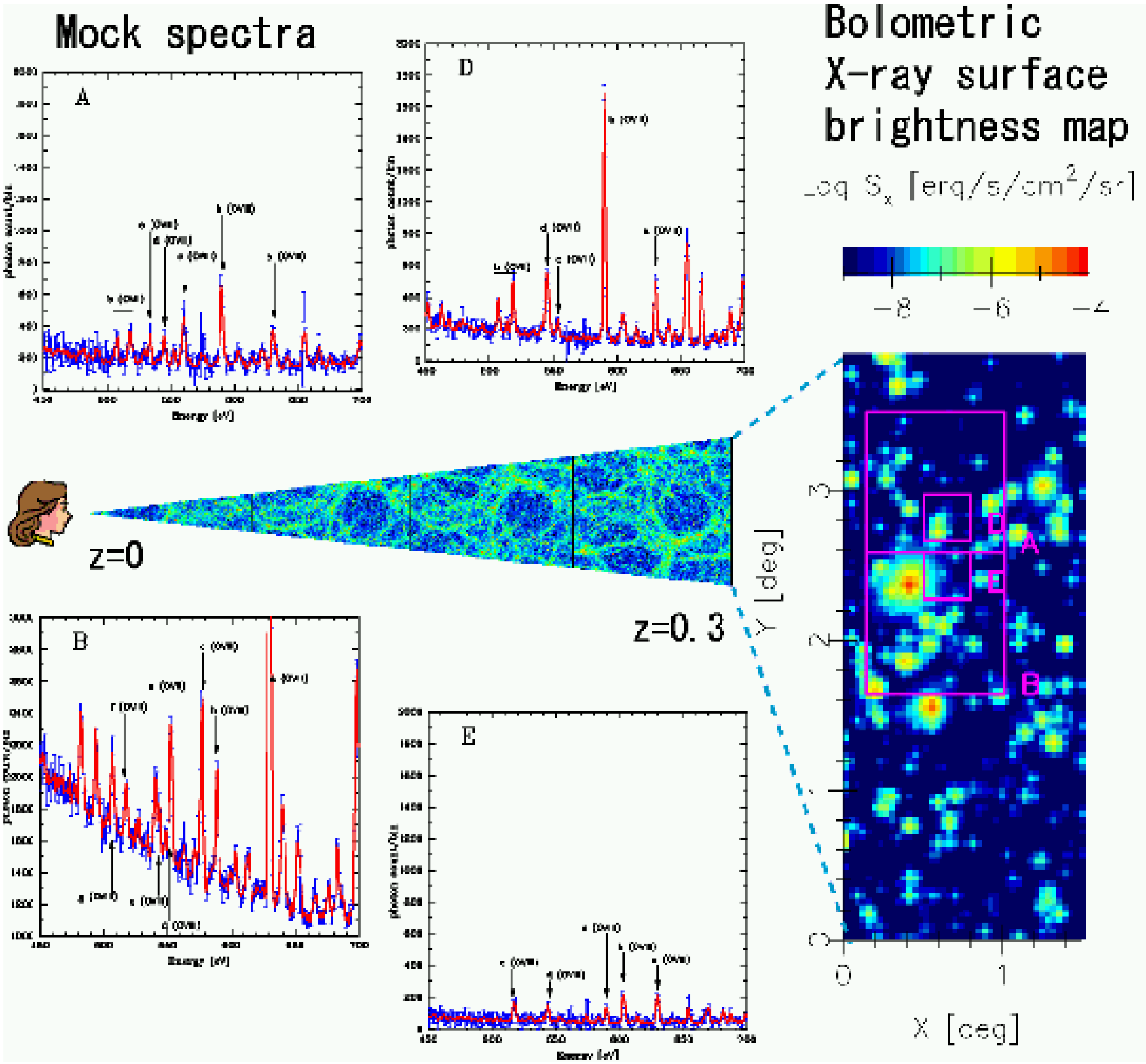


FIG. 5: Mock surface density maps for bolometric X-ray emissions and the corresponding high energy-resolution soft-X-ray spectra of WHIMs expected for *DIOS*.

## III. DETECTABILITY OF WARM/HOT INTERGALACTIC MEDIUM WITH DIOS

### A. Constructing mock spectra from cosmological hydrodynamic simulations

We have examined the detectability of WHIM through OVIII and OVII emission lines with *DIOS* in detail previously [7] assuming a detector which has a large throughput $S_{\rm eff}\Omega = 10^2$ cm$^2$ deg$^2$ and a high energy resolution $\Delta E = 2$ eV. Here we briefly summarize those results.

First we create the simulation lightcone data over the $5^\circ \times 5^\circ$ region of a sky up to $z = 0.3$ (see Fig.5); we put $64 \times 64$ square grids on the celestial plane and 128 equally-spaced bins along the redshift direction. We compute the surface brightness of each cell on the $64 \times 64 \times 128$ grid, and integrate along the same line of sight. The emissivities of OVII and OVIII lines (Fig. 6) are computed assuming the collisional ionization equilibrium. For simplicity, the metallicity is set to be $Z = 0.2Z_\odot$ independently of redshifts and the densities of the intergalactic medium. This procedure yields the projected surface density map ($64 \times 64$ pixels) on the celestial plane.

Similarly we construct the corresponding mock spectra at soft X-ray energy band ranging from 450eV to 700eV along each line of sight. Figure 7 shows examples of the template spectra that we adopt. At a lower temperature, $T = 10^6$ K, we have strong emission lines of the OVII triplets ($E = 561, 568, 574$ eV). Around $T = 10^{6.5}$ K and $10^7$ K, OVIII line at $E = 653$ eV and many Fe XVII lines at $E > 700$ eV become prominent.

The upper panel of Figure 8 shows an example of the

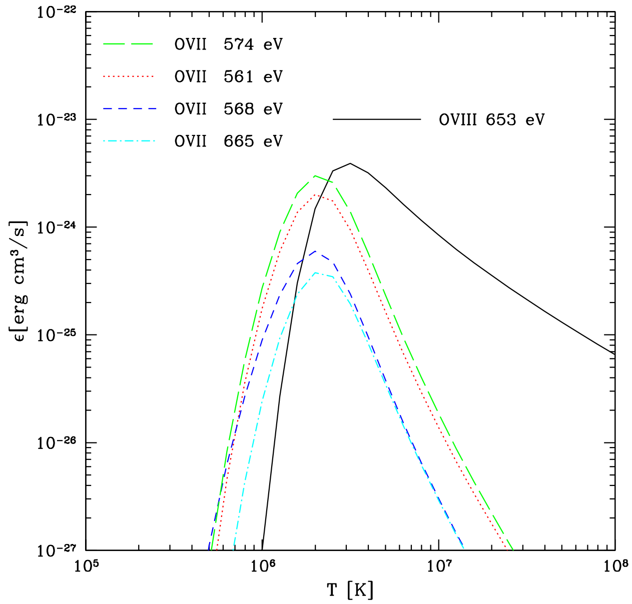


FIG. 6: Emissivity of OVII and OVIII lines in collisional ionization equilibrium.

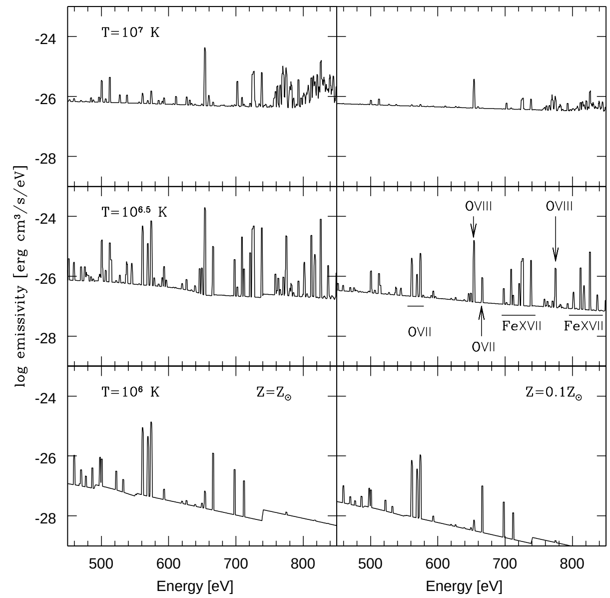


FIG. 7: Template spectra of collisionally ionized plasma with temperature $T = 10^6$ K (*lower panels*), $10^{6.5}$ K (*middle panels*), and $10^7$ K (*upper panels*). Spectra for metallicity $Z = Z_\odot$ and $Z = 0.1Z_\odot$ are shown in the left and right panels, respectively.

simulated composite spectrum, which includes the contribution from WHIM, Cosmic X-ray Background, the Galactic emission lines, with exposure time $T_{\rm exp} = 3\times10^5$ sec for the region A (0.88 deg$^2$) in Fig. 5. Strong lines in the upper panel correspond to the Galactic emission lines of NVII at 498 eV, OVII at 561eV, 568 eV, 574 eV, and 665 eV, and OVIII at 653 eV. Clearly the separation of the Galactic component from the WHIM emission lines is the most essential. In order to mimic the realistic separation procedure, we construct an independent realization of spectra which consists purely of the CXB and Galactic emission lines but using the different sets of random numbers in adding the Poisson fluctuations in each bin. Then the latter spectra are subtracted from the mock spectra (WHIM + CXB and Galactic emissions), which yields a residual mock spectrum purely for the WHIM (*dots with Poisson error bars in lower panel*). For comparison, we plot the noiseless WHIM spectrum from simulation in solid line. The emission lines with labels in the lower panel indicate OVIII and OVII triplet lines whose surface brightness exceeds the expected limiting flux of *DIOS*. Thus this plot indicates that the emission lines exceeding the residual photon number $\sim$ 100 counts/bin are detectable with a three-day exposure.

### B. Results

Figure 5 summarizes the mock imaging map and the corresponding spectra for the *DIOS* survey. Since WHIM is supposed to reside in the outskirts of galaxy clusters and/or in galaxy groups, it is quite natural to select vicinity of rich galaxy clusters as target regions. Thus we select the regions A and B for shallower exposure ($T_{\rm exp} = 3\times10^5$ sec, field-of-view of 0.88 deg$^2$, and $S_{\rm eff}\Omega T_{\rm exp} = 3\times10^7$ cm$^2$ deg$^2$ sec) and D and E for deeper exposure ($T_{\rm exp} = 10^6$ sec, field-of-view of 0.098 deg$^2$, and $S_{\rm eff}\Omega T_{\rm exp} = 1.1\times10^7$ cm$^2$ deg$^2$ sec).

The region B encloses an X-ray cluster located at $z = 0.038$, and the region A contains a filamentary structure around the cluster (Fig. 5). The spectra along the region B exhibit a strong OVIII emission line at $E = 629$ eV, which originates from the intra-cluster medium of the X-ray cluster at $z = 0.038$. The OVII triplet emission lines around $E = 535 - 560$ eV are also ascribed to the same cluster. The region D shows an emission line due to a substructure of a cluster at $z = 0.039$. The spectra in the regions D and E show the emission lines from the galaxy cluster and its substructure at $z = 0.039$. We note that the emission line in the region D corresponding to the $z = 0.039$ structure is stronger than the counterpart in the region E, although the temperature of the region D at $z = 0.039$ is $\simeq 7\times10^6$ K and in fact lower than that of the region E ($\simeq 2\times10^7$ K). This is because the emissivity of OVIII decreases as the temperature exceeds $T \approx 3\times10^6$ K, and clearly demonstrates that the oxygen lines are more sensitive to the presence of the WHIM than that of the higher temperature gas associated with intra-cluster gas.

Figure 5 indeed demonstrates that the high-spectral resolution of *DIOS* enables to identify the WHIM at dif-

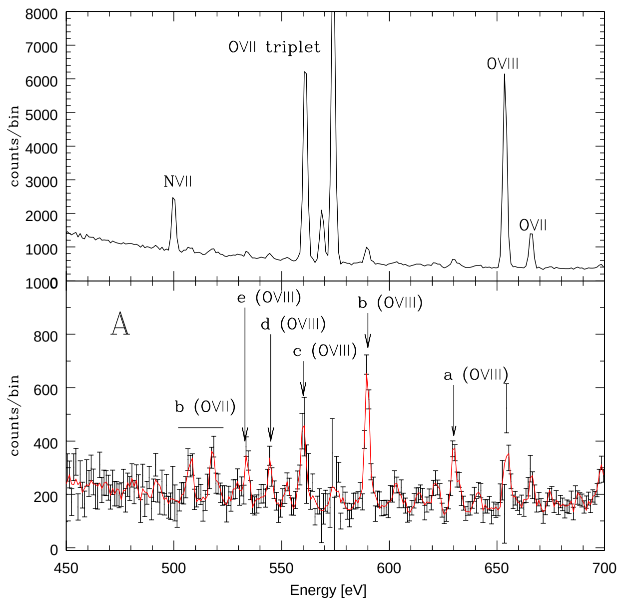


FIG. 8: A simulated spectrum along a line of sight. *Upper panel* shows emission lines of WHIM, the CXB and the Galactic emission. *Lower panel*: The spectrum of WHIM after the CXB and the Galactic emission are subtracted. The constant metallicity of $Z = 0.2Z_{\odot}$ is adopted.

ferent emission energies, i.e., Oxygen emission line tomography of the WHIMs at different locations.

### C. Observational strategy

The previous subsection indicates that a single pointing needs typically 100 ksec to obtain enough oxygen photons from WHIM. Figure 9 shows the expected pulse-height spectrum of 0.2keV plasma when 1000 photons of oxygen emission lines are collected. We expect that this quality of data can be obtained from surrounding regions of clusters of galaxies with 100–300 ksec of observation. For large-scale filaments, roughly 10 times less photos are expected for the same observing time. On the other hand, the hot interstellar medium in our galaxy produces an order-of-magnitude stronger line emission. With this data quality, the lines in the OVII triplet are clearly detected and we will be able to measure the temperature of the WHIM directly. These three lines can also be used to separate individual plasma components when several emission regions with different redshifts overlap along the line of sight.

Effective observing time will be approximately 40 ksec for a near earth orbit. So if one integrates for 100 ksec in each pointing position, a sky map for an area of $10^{\circ} \times 10^{\circ}$ can be produced in a year. This size of the survey area is sufficient to trace the large-scale structure of the universe at $z < 0.3$. This survey observation of a limited sky will

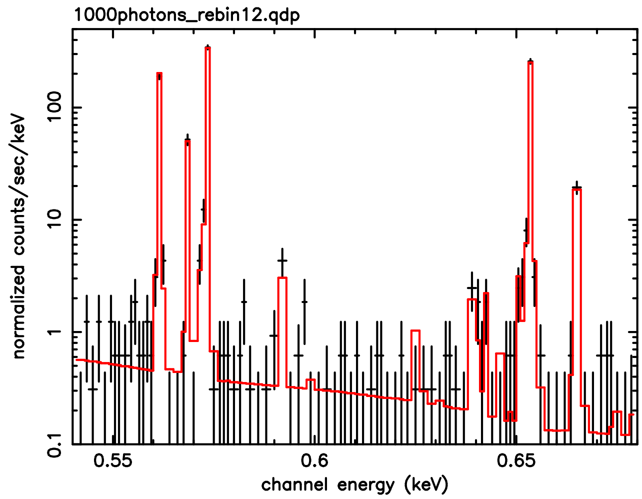


FIG. 9: Pulse-height spectrum for OVII and OVIII lines expected with *DIOS* from a plasma with $kT = 0.2$ keV when 1000 line photons are accumulated.

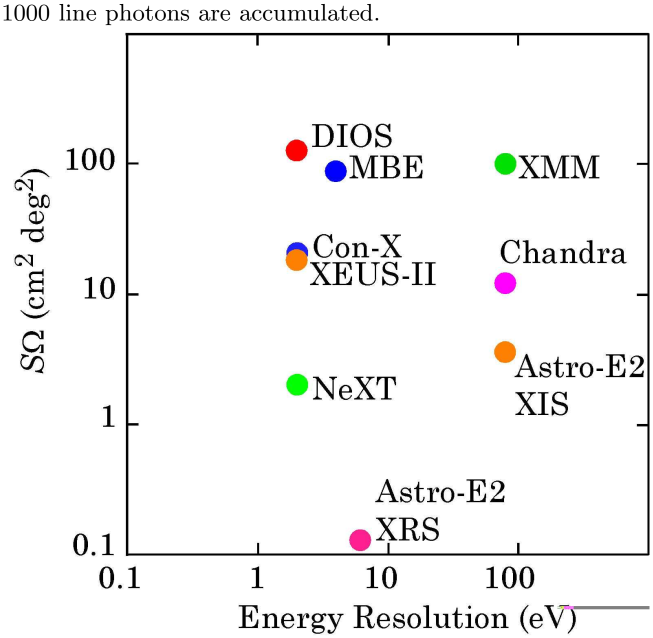


FIG. 10: Comparison of $S\Omega$ and energy resolution for spectroscopic instruments (CCDs and micro-calorimeters) for planned and operating X-ray satellites.

be the first task of *DIOS*. Since oxygen lines from the galactic interstellar medium are stronger by roughly 2 orders of magnitude, 1 ksec in each point is good to make a large map of the interstellar medium distribution. We plan to devote the second year for a survey of a $100^{\circ} \times 100^{\circ}$ sky for the Galactic interstellar medium. After these 2 years, further deeper observations of the intergalactic medium as well as of the outflowing hot gas in near-by galaxies can be performed.

Figure 10 compares $S\Omega$ and energy resolution among different instruments in the X-ray missions which are planned or already in operation. Clearly, *DIOS* will

achieve the highest sensitivity for soft X-ray lines from extended objects. We believe that *DIOS*, with its complementary performance to larger general-purpose X-ray missions, will bring very rich science on cosmological evolution of baryons.

## IV. CONCLUSIONS

We have presented our recent proposal of a dedicated soft-X-ray mission, *DIOS* (Diffuse Intergalactic Oxygen Surveyor). Within the exposure time of $T_{\rm exp} = 10^{5-6}$ sec *DIOS* will be able to reliably identify Oviii emission lines (653eV) of WHIM with $T = 10^{6-7}$ K and the overdensity of $\delta = 10^{0.5-2}$, and Ovii emission lines (561, 568, 574, 665eV) of WHIM with $T = 10^{6.5-7}$ K and $\delta = 10^{1-2}$. The WHIM in these temperature and density ranges cannot be detected with the current X-ray observations except for the oxygen absorption features toward bright QSOs. *DIOS* is especially sensitive to the WHIM with gas temperature $T = 10^{6-7}$K and overdensity $\delta = 10-100$ up to a redshift of 0.3 without being significantly contaminated by the cosmic X-ray background and the Galactic emissions. There is a similar proposal called Missing Baryon Explorer (MBE) in the U.S. [10]. *DIOS*, hopefully launched in several years, promises to provide yet another important and complementary tool to trace the large-scale structure of the universe via dark baryons.

### Acknowledgments

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